

## The Utility of Volume-Based Static Cell Models

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## 1. Introduction

Generalized models will be presented to help understand the volume-related issues of four different cell chemistries used in aerospace battery applications: nickel cadmium, nickel hydrogen, silver zinc, and lithium-thionyl chloride. In addition, examples will be given of how the models were used to investigate problems or questions in actual applications. This modeling technique has also been useful in understanding the volume-related, and thus the weight-related, impacts of different potential cell designs before a commitment has been made to construct actual cell hardware. This is particularly important in the field of nickel-hydrogen cells, where there are over 100,000 different combinations and permutations of cell components available to the cell designer. The results of these general modeling principles are only useful as they are applied to volume-related cell problems or questions. Other cell problems, such as those related to pore sizes, distribution of active material within the pores of the electrode substrate, contaminants, and migration, are beyond the scope of these models.

The models require the accurate knowledge of each component's dimensions, specifications, tolerances, and porosities. The specific gravities of the components are also used in the calculations. A bookkeeping record of all the volumes of interest is then made, along with the inside dimensions of the cell and the amount of electrolyte that is added during the filling procedure. Nickel-cadmium cells are usually designed to not have electrolyte in excess of the quantity held within the wettable pores of the components themselves. This condition is referred to as being "starved." At the opposite end of the spectrum, lithium cells with liquid cathodes have electrolyte in excess of the amount that can be contained within the pore structure of the plate pack. Nickel-hydrogen cells at times are designed to have liquid electrolyte outside of the plate pack and in communication with it via the capillary forces of the wall wick. Silver-zinc cells usually have a small amount of free liquid in them. In the three alkaline chemistries, the electrolyte functions as a reservoir of hydroxide ions and also as the conductive ionic pathway between the anodes and cathodes of the cell. The reader is referred to other sources to better understand the intricacies of these four cell chemistries (Refs. 1, 2). A common concern with all these cell types is to have the proper electrolyte concentration and quantity in the completed cell, so that it will operate properly over the entire course of its intended mission life. Some cell chemistries have an additional requirement related to the desired free volume remaining in the cell after they have been fully assembled, filled with electrolyte, and hermetically sealed. Of the four cell types being considered here, silver-zinc cells are the only ones that are not hermetically sealed. They are equipped with low pressure (2-3 psid) vent valves that are intended to permit the buildup of hydrogen gas to escape from the cell. Unfortunately, these valves also permit electrolyte to escape as well under certain circumstances.

The following sections will briefly describe the particular problem or concern that initiated the development of a chemistry-specific, static model, and the major components that are required for the completion and exercising of the model. Following this description, several examples will illustrate the utility of results that depend only on the volumetric aspects of the cell design.

Except for the nickel-hydrogen model, the other three models only deal with the initial design and beginning of life (BOL) issues. The nickel-hydrogen model incorporates known changes that occur over the course of cycling as they impact electrolyte volume and concentration requirements. Where available, references that discuss each of these models in greater detail will be cited. Because the examples given at the end of each section are intended to show trends and the utility of this modeling method, there was no need to use proprietary information. Cells that are well known in terms of number of plate and physical dimensions have been used for convenience only. It is not intended to imply that these designs are available from any manufacturer.

## 2. Nickel Cadmium

The static model developed for aerospace nickel-cadmium cells was initiated to assist in determining the reasons for a series of problems with certain cell lots. These cell lots were originally designed and manufactured by General Electric's Battery Business Division. One of the series of designs was known as the NASA Standard Designs. Another design, current in the 1970s and 1980s, was a lightweight version of that series, advertised to have a higher BOL energy density. The NASA cells were built to a very exacting set of specifications and tolerances that had been found to yield excellent results in life cycle testing. When cells were built to these specifications, the amount of electrolyte added during activation was about 3.0 ml of KOH solution for each ampere-hour (Ah) of nameplate capacity. When the internal volumes of the cells were all calculated, this amount corresponded to a fill factor of about 75%.

The modifications that led to problems with these cells in the late 1980s are clearly outlined in the NASA report authored by Mr. Floyd Ford (Ref. 3), who was closely associated with these cells and batteries before his retirement. The three main modifications detailed in that document will only be listed below. The lot rejection problems were more evident with the lightweight family of cells. For this cell chemistry, the static model begins with the interior dimension of the rectangular parallelepiped into which the cell components are placed. Each item placed into the cell takes away from the remaining free volume. The first modification was made to increase the BOL energy density. To do this, the manufacturer began to increase the plate loading of active material. A second modification was added to increase the strength of the finished nickel plate. This was accomplished by a passivation process that reduced the amount of nickel corrosion that took place during the chemical impregnation step of the positive plates. This left the finished plate with a reduced amount of free volume. The third modification, which was forced upon the manufacturer, was the change in the separator material. Materials with a higher weight-per-unit area had to be substituted for the previously used material. All three of these modifications reduced the amount of free volume within the completed cell.

The important inputs for this model are: (1) the thickness, dimension, and the initial and final coated weights of the plaque material that forms the substrate into which the metal hydroxides are chemically impregnated; (2) the loading levels of hydroxide and any accompanying additives; (3) the dimensions and weight-per-unit area of the separator material; and (4) the number of plate pairs (one extra cadmium plate), and nameplate capacity, along with all the cell internal dimensions and the component densities. The model requires a fill factor (typically 75%) to be inserted and then calculates the milliliters of electrolyte per ampere hour (Ah) of cell capacity. It also calculates the percentage of nickel attack, grams of active material loading per cubic centimeter of void volume within the electrode, hydrate-to-nickel ratio for both plate materials, and the free volume within the cell prior to being filled with electrolyte.

With the constant decrease in available void volume, the traditional fill factor resulted in electrolyte quantities farther and farther below the desired number of about 3 ml/Ah. When fill factors were increased, the cell pressures during the overcharge testing were too high. Activating these cells became difficult, and lot rejections became more frequent.

To illustrate the utility of the model, several examples will be given. In Table 1, the summary results of four cell designs are given. They show the progressive reduction in electrolyte quantity as the three manufacturing modifications were made. The first example cell, which is very close to what was called the Air Force Light-Weight 35, has 13 nickel plates and 14 cadmium plates. The three modifications listed previously will be considered here. These modifications, which will illustrate the impact on the manufactured cells, will be (1) an increase in the amount of active material placed within the plates during the impregnation step by 10%, (2) a change in the separator material from the one traditionally used with a weight-per-unit area of 60 gm/m<sup>2</sup> to the alternate at 80 gm/m<sup>2</sup>, and (3) the introduction of a passivation step in the production of the plaque material used for the nickel electrodes.

**Table 1. Electrolyte per Unit of Capacity at a Constant Fill Factor as Manufacturing Conditions Changed**

Cell Design	Separator Weight-gm/m <sup>2</sup>	Passivation Process	Plate Loading Level	Fill Volume-ml/Ah
Cell 1*	60	no	low	2.47
Cell 2	60	yes	low	2.33
Cell 3	80	yes	low	2.24
Cell 4	80	yes	high	2.20

\* "Original design."

In a second example cell, the model will be used to estimate the changes made to the cell design, starting with Cell Design 4. Several design changes were requested by a customer in an attempt to find the proper balance between the amount of electrolyte and the amount of void volume in the completed cells. Free volume is important for the recombination process, where oxygen gas recombines chemically on the surface of the charged portion of the cadmium electrode. In an experiment that has not appeared in the open literature, the cell manufacturer made available three groups of cells that were identical, with the exception that the first group had the prescribed number of plates and the prescribed amount of electrolyte as suggested by the cell manufacturer, the second was filled with 5% less electrolyte, and the third had one less



plate pair with 5% more electrolyte than that prescribed for the standard cells. The results of the life cycle testing showed that the cells with a full set of plates and the prescribed amount of electrolyte had a very short cycle life due to electrolyte and pack compression problems (about 2000 cycles). The cells with one plate pair removed cycled to about 20,000 cycles but gave some indication that there was an insufficient amount of pack pressure. The cells that were "underfilled" in terms of the recommended amount of electrolyte worked best (about 30,000 cycles to failure). The results of this experiment illustrate the critical balance between the amount of electrolyte and the required amount of free space within an operating cell. With one plate pair removed, the one group of cells was operating at a higher current density since about 8% of their original plate area had been removed. Table 2 tabulates the changes in the electrolyte fill amounts for these three different cell groups using a representative cell design, but one that is different than the one used in the actual experiments. In just a few minutes, the impact of changes in loading levels, separator area weights, and electrolyte fill quantities on the cell fill factor and electrolyte quantities per unit of capacity can be explored via a single one page spreadsheet.

Note that information about this experiment was provided by and used with the permission of Mr. Robert Richards, now retired from Martin Marietta, Denver.

**Table 2.**

**Changes in Fill Amounts in Modified Cell Designs**

Cell Number	Plate Pairs	Plate loading	Fill Factor	Electrolyte	ML/Ah
Cell 4	13	High	0.75	82 MI	2.33
Cell 5	13	High	0.72	78 MI	2.24
Cell 6	12	High	0.72	86 MI	2.46

### 3. Nickel Hydrogen

The nickel-hydrogen model was developed to explore the changing electrolyte requirements of these cells as impacted by the physical and chemical changes that are known to take place over the course of their cycling history. Nickel-hydrogen designs first began to be tested in the 1970s, and commercial use began in the 1980s. Because of the tremendous amount of cycling data and technical reporting in the open literature, the degradation modes affecting the electrolyte requirements and distribution are fairly well understood. In reviewing the amounts of electrolyte that were added to each cell during the filling process and in following the subsequent performance history, it would appear there are cell designs that were filled with insufficient amounts of electrolyte and others that were overfilled. As with nickel-cadmium designs, there is a rather narrow spread in the amount of electrolyte that a cell can tolerate while still performing well. The nickel-hydrogen model focuses on the percentage of the wettable pores within a cell that are filled with electrolyte, coupled with the degradation processes that alter the distribution of electrolyte over the course of cell cycling. These processes include plaque corrosion, plate expansion, and gamma phase formation. This model is also helpful in assessing the value of proposed cell designs before they are built. The model centers on the wettable void volumes of the electrodes and the separator material. These cells are "starved" compared to nickel-cadmium cells, which are also classified as being starved. It is not uncommon for nickel-hydrogen cells to be designed so that when they are filled with electrolyte, activated, and sealed off, they still have less than 100% of the wettable pores filled with electrolyte.

The static model for this cell type first incorporates all the usual dimensions of the different cell components and the specific gravities of the different materials. Recent publications describe the finer points of this model in much more detail (Refs. 4, 5). Once the model is set up as a spreadsheet, a value for the percentage of plaque corrosion that might occur over the course of the expected cycle life is assumed. Assumed values for the plate expansion due to cycling stresses are then made, as well as estimates of the amount of gamma material that will be formed as a consequence of the cycling environment. Changes in the percentage of separator pores that are filled with electrolyte are then calculated by the model. This calculation permits estimates to be made of the volume tolerance of this particular cell design. These results would alert the cell designer or the potential purchaser to problems that may arise during extended cycling. The model will calculate the distribution of electrolyte between the electrodes and the separator. The nickel electrode is assumed to be fully saturated with electrolyte, and the wettable portion of the hydrogen electrode (~25% of the gross volume) is also assumed to be filled with electrolyte. Due to the relative pore size character of the three components of the stack, any deficiency in electrolyte appears in the separator since it has the largest pore sizes. The model calculates these numbers at the BOL. It also calculates the impact on electrolyte distribution caused by corrosion, plate expansion, and gamma phase formation, separately and then in combination with each other.

Several different cell examples will be reviewed by creating a generic 62 plate pair, 3.5 in. individual pressure vessel cell, based on numbers that are either available in the open literature or used as assumptions. These examples are summarized in Table 3. Of the three different factors that impact the electrolyte requirements, plate expansion is the most significant. Due to the pore character of the nickel electrode relative to the separator materials, electrolyte is withdrawn from the separator and absorbed into the nickel electrode. Of lesser importance, but factored into the model, are the effects of plaque corrosion and gamma phase formation. One aspect of gamma phase formation that must not be neglected is its ability to reduce the concentration of KOH as it becomes incorporated into its lattice structure of the active material. This factor is built into the model as well. For this reason, the changes in electrolyte concentration are also estimated. The results from the model based on this generic cell will be used to illustrate what changes take place when plate expansion occurs. A single-layer Zircar separator will be used in three of the cells. For comparison, a sample calculation will be shown for the more usual combination of two layers of Zircar and 31% KOH. The numbers for this cell design point out the weight penalty paid for the very tolerant and forgiving features of the double-layer Zircar design.

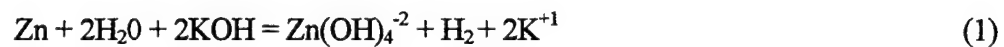
**Table 3.**  
**Changes in Separator Fill Percentages and Concentrations**  
**for Three Different Cell Designs\***

Cell No.	Cell 7	Cell 8	Cell 9	Cell 10
Features	31% KOH, 12% Expansion	26% KOH, 12% Expansion	26% KOH, 5% Expansion	31% KOH, 12% Expansion
Name-Plate Cap. - Ah	75	70	70	75
Electrolyte Fill - 90%	250	240	240	350
Gm/Ah	3.3	3.4	3.4	4.6
Sep. Fill BOL - %	77	77	77	86
Sep. Fill EOL - %	32	33	52	80
Final KOH Conc. - %	29	24	24	29
Possible Problems	Separator Fill	Separator Fill & Conc.	Separator Conc.	None

\*Corrosion assumed to be 5%, and gamma phase formation, 50% of maximum.

#### 4. Silver Zinc

The silver-zinc model was developed to investigate the electrolyte loss phenomenon that occurs with hand-activated, primary batteries, such as those used on launch vehicles (Refs. 6, 7). Electrolyte loss from activated cells is caused by several factors. The major ones are due to the reactivity of the zinc electrodes, especially if they have not been properly amalgamated. Even when properly amalgamated, there will be some degree of reaction with the water in the electrolyte, as in Eq. (1). The rate of hydrogen evolution diminishes with time as the surface area of the porous zinc structure becomes oxidized.



Silver-zinc cells that are used in batteries for launch vehicle applications are not hermetically sealed. A vent valve located on the top of the cell (Figure 1) opens at a differential pressure of 2 or 3 psid to release the buildup of hydrogen gas that results according to the reaction depicted in Eq. (1). The hydrogen formed on the surfaces of the porous zinc electrode structure can displace electrolyte from the interior of the electrode and thereby alter the liquid level within the cell. Zinc electrodes are very porous (50%-70%) and represent one of the major porous volumes within a cell. The displacement of electrolyte out of the zinc electrodes and into the cell free volume can result in electrolyte being forced out through the vent valve under conditions where there is an insufficient amount of free volume above the plate pack and below the entrance of the vent valve. It is also possible for escaping bubbles of hydrogen to carry out small droplets of electrolyte as they disengage from the bulk electrolyte and escape through the vent valve. Electrolyte that is outside of the cells and inside of the battery box has been known to cause problems. These problems are minimized by waiting for the reactivity to the zinc to subside before subjecting the inside of the cells to the final application of a mild vacuum. This step facilitates the removal of any trapped hydrogen within the pore structure of the zinc electrodes. Following this step, the vent valves are reinstalled, the battery box is closed, performance checks are made, and finally, the battery is installed on the launch vehicle.

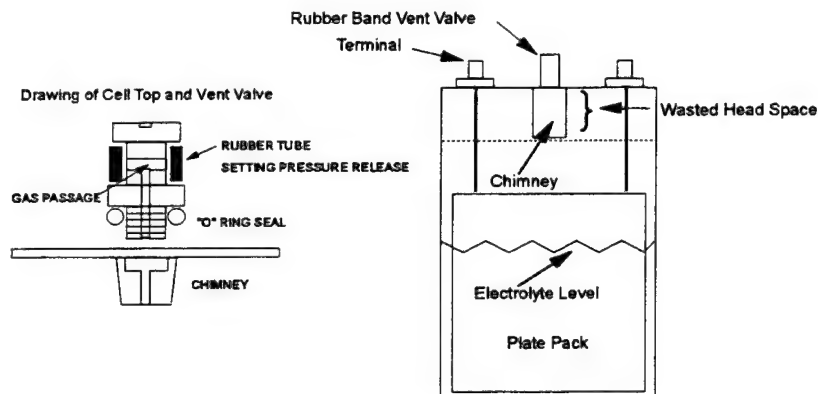


Figure 1. Schematic showing features of a typical silver-zinc cell.

Silver-zinc cells all have the majority of the electrolyte absorbed within the pore structure of the electrodes, the cellulosic separator, and the wettable woven and nonwoven absorber materials that form part of the separator system or shock absorber side and bottom pads. There has been a desire to increase the activated stand time of these cells in order to reduce the number of change-outs on the vehicle caused by launch delays and short wet-life limitations. One way to increase the stand time is to increase the amount of electrolyte that is added to the cell during the activation process. The extra electrolyte has been found to reduce the rate at which potassium oxalate crystals form. These crystals have been known to perforate the cellulosic separator material, resulting in a short circuit within the cell. These newer cells will have less free volume once the electrolyte quantity has been increased, unless the height of the cell case is increased. If the activation procedure does not employ adequate levels of vacuum during the filling and redistribution steps, and the zinc electrodes have not been properly amalgamated, the electrolyte can be forced out of the pores of the zinc electrode and raise the level of free electrolyte to the point that it will be forced out the cell vent valve.

The silver-zinc model was constructed to evaluate different cell designs in regard to the possibility that bulk electrolyte loss could take place. The model calculates the free volumes within the cell, along with the percentage of the pores within the zinc electrodes that can be emptied before the electrolyte begins to be pushed out of the top of the cell. The model starts with the interior dimensions of the rectangular cell case (gross interior free volume), and then subtracts the volume at the top of the cell that is wasted due to the protrusion of the vent chimney into the cell volume (Figure 1). From this quantity (the cell's net interior free volume), all of the volumes and porosities of the components are calculated, and the solid volumes are summed and then subtracted to yield the gross free volume. Finally, the volume

of the electrolyte to be added during the activation step is subtracted to yield the net free volume. This number assumes that the pores of all the wettable materials will absorb electrolyte up to the full capacity of their pore volume. The electrolyte is generally assumed to be absorbed within the wettable porosity of the different electrode and separator materials. The minimum free electrolyte volume represents the difference in the volume of electrolyte that is added to the cell and the total volume of all the pores of the various cell components. A negative number indicates that there is a larger volume associated with the porous materials than volume associated with the added electrolyte volume. However, some of the pores may be empty, due either to the fine pores not being filled with electrolyte during the vacuum backfilling process, or to the displacement of the electrolyte by hydrogen due to the reactivity of zinc. The next calculation determines the percentage of the pores of the zinc electrodes that can be emptied of electrolyte and still maintain the liquid level below the bottom of the vent chimney. A value larger than 100% suggests that it is impossible for electrolyte to be forced out of the cell from this phenomenon. If this number is less than 100%, then care must be taken to be assured that the reactivity between the zinc and the electrolyte has subsided and that this subsidence has been followed by one or more vacuum applications to remove as much trapped hydrogen as possible prior to the final installation of the vent valves.

Table 4 shows the results of these studies when applied to four different cell designs that were produced by two different manufacturers. It should be noted that two of the cell designs have the potential for expelling bulk quantities of electrolyte. Care must be taken during the activation procedure of batteries using these cells.

**Table 4.**  
**Tolerance to Changes in Free Electrolyte Volumes of Several Cell Types**

CELL PARAMETER	CELL TYPE			
	CELL-A	CELL-B	CELL-C	CELL-D
Porosity of Zinc Plates - %	69	67	63	58
Gross Cell Interior Volume - cm <sup>3</sup>	394	85.6	63	21
Net Cell Internal Volume - cm <sup>3</sup>	359	77	57	19
Gross Free Volume - cm <sup>3</sup>	218	47	39	11
Electrolyte Fill Volume - cm <sup>3</sup>	174	35	23	8.5
Net Free Volume - cm <sup>3</sup>	44	12	16	2.8
Minimum Free Electrolyte Volume - cm <sup>3</sup>	1.1	-0.7	-4.1	2.0
Permissible Loss From Zn Plates - %	41	80	163	114

## 5. Lithium-Thionyl Chloride

The model for the lithium-thionyl chloride cell also addresses electrolyte volume issues, but from a different perspective. It was developed to explore the impact of tolerance buildup of cell components on the span in free volume that can be present in a group of fully assembled and hermetically sealed cells. Cells of this type have been manufactured for applications of the U.S. Air Force (Refs. 8, 9, 10) and as part of the European Space Agency's Manned Space Transportation Program (MSTP) technology effort ( Ref. 11). Large cells of this type are equipped with burst disks that are set to open if the cell temperature would ever exceed a certain limit. The burst disk is set to release at a set pressure that can be related to the interior temperature if all of the contributing factors are known. Since the gas/vapor in the free volume within the cell is made up of thionyl chloride, sulfur dioxide, and the cover gas, the pressure above the liquid will be a function of its composition and the state of charge of the cell. The thermal coefficient of expansion of the electrolyte is a complicating factor as well. The pressure at any one time inside the cell, as a first approximation, will be a function of the amount of capacity withdrawn from the cell, the initial free volume within the cell, the degree of equilibration of the electrolyte with the vapor, and the temperature. Tolerance buildup in the many components within the cell impacts the span in the initial free volume, which, in turn, will result in a span of the expected burst disk opening temperature. Because the cell will become inactive once the burst disk has opened, it would be undesirable to have the cell vent prematurely, at a temperature still within the safe operating range of these cells. On the other hand, it would be more undesirable to not vent if the cell were to exceed its safe operating temperature. This temperature is usually considered to be safely below the melting point of lithium (161.5°C). This model focuses on the manufacturing tolerances in terms of plate thickness, fill volumes, and interior dimensions of the cell container that impact the free volume within the cell after the electrolyte is added. The cell that was used for the model has been manufactured for applications, as described above. Table 5 lists some of the features of this cell, as described in the literature references.

The dimensions and tolerances used to develop the model have yet to appear in the open literature, so only the methodology can be described. Since the cell container acts as a pressure vessel, its interior volume is the starting point from which the effective volumes of all the components are subtracted. To subtract these volumes, engineering drawings of the individual components are required. Once all the internal volumes are calculated, with the aid of the specific gravity of the different components, the free volume prior to filling can be calculated. With the subtraction of the volume taken up by the electrolyte, the nominal free volume of the cell can be calculated. An ullage band (span of void volumes in a filled cell) on either side of the nominal value is next calculated, based on the tolerances placed on the different cell components. The carbon cathode is a highly porous structure, with approximately 80% voids, according to literature values cited by other manufacturers. The thickness estimate was made using information relating the grams of carbon/Teflon mixture requirements as a function of current density. This information was developed by other workers in the field of lithium-thionyl chloride. Because of the approximately 80% porosity of



the cathode, a tolerance limit of 1 unit on the cathode is multiplied by a factor of 4 if the anode has the same 1 unit of tolerance associated with its thickness. Once the band of void volumes is calculated, the relationships between volume-temperature-depth of discharge are reviewed in order to determine the span in burst temperature.

**Table 5.**  
**Characteristics of the SAFT VLS 250 AM Cell**

Nominal Capacity - Ah	250
Lithium Capacity - Ah	350
Carbon Capacity - Ah	275 (at design current density)
Thionyl Chloride Capacity - Ah	500
Number of Lithium Electrodes	49
Number of Carbon Electrodes	48
Total Surface Area of Lithium - cm <sup>2</sup>	7919
Area per Plate - cm <sup>2</sup>	81 (on each side of plate)
Nominal Dimensions if Square - cm	9 x 9
Nominal Thickness - mm	~0.5 (from size and capacity data)
Current Density at 50 A Load - ma/cm <sup>2</sup>	6.3 (total area)
Current Density at 20 A Load - ma/cm <sup>2</sup>	2.5 (total area)
Nominal Thickness - mm	~0.86 (assuming 2 Ah/gm and 80% porous)*

\* Based on information in Reference 6.



## 6. Summary

The methodologies used in developing four similar but different volume-based static cell models have been described, along with examples of how they can be used. These models were first developed to help resolve performance and life issues or to help understand volume-related aspects of different cell designs. In applying these models to actual cell designs and issues, the interactions between electrolyte fill amounts and performance became more clear. For older nickel-cadmium cell designs, where a series of manufacturing modifications were initiated, the progressive reduction in electrolyte fill volumes could be charted. None of the models described here can address the electrochemical questions of why performance degrades with less than optimum amounts of electrolyte. In the nickel-hydrogen technology, the adverse impact of having too much or too little electrolyte at BOL becomes more clear. This impact results in life and performance problems as cells progress into extended life cycle testing. With the silver-zinc model, it is now understandable why certain cell designs are more subject to electrolyte loss problems than others. Finally, the possible span in free volume in completed thionyl-chloride cells was estimated as a first step towards estimating the span in burst disk pressures as impacted by the dimensional tolerances of the components used in manufacturing the cells. These models and methodologies can also be used to explore volume-related aspects of proposed new cell designs before they are committed to hardware.

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## TECHNOLOGY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Technology Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual Technology Centers:

**Electronics Technology Center:** Microelectronics, VLSI reliability, failure analysis, solid-state device physics, compound semiconductors, radiation effects, infrared and CCD detector devices, Micro-Electro-Mechanical Systems (MEMS), and data storage and display technologies; lasers and electro-optics, solid state laser design, micro-optics, optical communications, and fiber optic sensors; atomic frequency standards, applied laser spectroscopy, laser chemistry, atmospheric propagation and beam control, LIDAR/LADAR remote sensing; solar cell and array testing and evaluation, battery electrochemistry, battery testing and evaluation.

**Mechanics and Materials Technology Center:** Evaluation and characterization of new materials: metals, alloys, ceramics, polymers and composites; development and analysis of advanced materials processing and deposition techniques; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle fluid mechanics, heat transfer and flight dynamics; aerothermodynamics; chemical and electric propulsion; environmental chemistry; combustion processes; spacecraft structural mechanics, space environment effects on materials, hardening and vulnerability assessment; contamination, thermal and structural control; lubrication and surface phenomena; microengineering technology and microinstrument development.

**Space and Environment Technology Center:** Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation; propellant chemistry, chemical dynamics, environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, and sensor out-of-field-of-view rejection.